Eksploatacja i Niezawodnosc – Maintenance and Reliability
Volume 23 (2021), Issue 3
journal homepage: http://www.ein.org.pl
Article citation info:
Wang Z, Yuan H. Enhancing machining accuracy reliability of multi-axis CNC machine tools using an advanced importance sampling method. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2021; 23 (3): 559–568, http://doi.org/10.17531/ein.2021.3.17.

Enhancing machining accuracy reliability of multi-axis CNC machine tools using an advanced importance sampling method

Indexed by: Web of Science Group

Zhiming Wang[a], Hao Yuan[a]

[a]School of Mechanical and Electronic Engineering, Lanzhou University of Technology, Lanzhou 730050, China

Highlights

- An accuracy allocation method for CNC machine tools is proposed.
- The error is presented by using the differential motion matrix and reliability theory.
- The machining accuracy reliability is given by an advanced importance sampling method.
- The effectiveness is validated by a CNC grinding machine.

Abstract

The purpose of this paper is to propose a general precision allocation method to improve machining performance of CNC machine tools based on certain design requirements. A comprehensive error model of machine tools is established by using the differential motion relation of coordinate frames. Based on the comprehensive error model, a reliability model is established by updating the primary reliability with an advanced importance sampling method, which is used to predict the machining accuracy reliability of machine tools. Besides, to identify and optimize geometric error parameters which have a great influence on machining accuracy reliability of machine tools, the sensitivity analysis of machining accuracy is carried out by improved first-order second-moment method. Taking a large CNC gantry guide rail grinder as an example, the optimization results show that the method is effective and can realize reliability optimization of machining accuracy.

Keywords

precision allocation, comprehensive error, machining accuracy reliability, sensitivity analysis, advanced importance sampling method.

Nomenclature

δ_{xx} *Positioning error of the X-axis*
δ_{yx} *Y direction of straightness error of the X-axis*
δ_{zx} *Z direction of straightness error of the X-axis*
ε_{xx} *Roll error of the X-axis*
ε_{yx} *Pitch error of the X-axis*
ε_{zx} *Yaw error of the X-axis*
δ_{xy} *X direction of straightness error of the Y-axis*
δ_{yy} *Positioning error of the Y-axis*
δ_{zy} *Z direction of straightness error of the Y-axis*
ε_{xy} *Pitch error of the Y-axis*
ε_{yy} *Roll error of the Y-axis*
ε_{zy} *Yaw error of the Y-axis*
δ_{xz} *X direction of straightness error of the Z-axis*
δ_{yz} *Y direction of straightness error of the Z-axis*
δ_{zz} *Positioning error of the Z-axis*
ε_{xz} *Pitch error of the Z-axis*
ε_{yz} *Yaw error of the Z-axis*
ε_{zz} *Roll error of the Z-axis*
S_{xz} *X and Z-axis perpendicularity error*
S_{yz} *Y and Z-axis perpendicularity error*
S_{xy} *X and Y-axis perpendicularity error*

1. Introduction

CNC machine tools integrate many technologies, such as accuracy machinery, electronics, electric drag, automatic control, automatic detection, fault diagnosis, and computer. It is a typical mechatronics product with high accuracy and efficiency [22]. Machining accuracy is critical to the quality and performance of machine tools and it is the first consideration of any manufacturer [20]. Machining accuracy reliability is the ability for machine tools can work normally to achieve the corresponding machining accuracy under specified conditions [14]. Its main influencing factors include geometric errors, thermal errors and cutting force errors, etc. Geometric errors and thermal errors are the main influencing factors, accounting for 45%-65% of the total errors. The higher the accuracy of machine tools, the bigger the proportion of geometric errors and thermal errors [12]. When the temperature changes to a stable state, the impact of geometric errors are the largest, accounting for about 40% of the total errors [5]. Large CNC gantry rail grinder has a wide range of travel and is suitable for heavy machinery, ships, and metallurgical equipment. This paper takes it as an example to analyze the relationship between geometric errors of components of the grinder and the reliability of grinding accuracy.

The accuracy design of machine tools includes two aspects: accuracy prediction and accuracy allocation [10]. Accuracy prediction

E-mail addresses: Z. Wang - wangzhiming301@sohu.com, H. Yuan - 2324996561@qq.com

refers to the prediction of the volume errors of a machine tool based on the known accuracy of the updated and maintained parts, and then the prediction of the machining accuracy of the workpiece [3]. Accuracy prediction is the basis of accuracy design. Error models are often used to predict the accuracy of machine tools. At present, the methods of establishing a comprehensive error model of machine tools include the matrix translation method, error matrix method, rigid body kinematics, and modeling method based on multi-body system theory [2]. Among them, modeling methods based on MBS theory are widely used, but the calculation amount is large and the process is complicated. In the process of modeling, the ideal position matrices, position error matrices, ideal motion matrices, and motion error matrices of components need to be considered at the same time. To reduce the amount of calculation, a geometric error modeling method based on differential motion relation of coordinate frames is adopted in this paper. By establishing the differential motion matrices between components, the transmission relationship between geometric errors of components and the comprehensive error of machine tools is determined.

Accuracy allocation refers to obtaining the accuracy of updated maintenance parts according to the total accuracy preset by the machine tool so that the accuracy of parts can reach the optimal scheme [17]. Its main content is to establish the reliability model of machining accuracy and the sensitivity model of machining accuracy reliability. There are many important methods of reliability and sensitivity analysis such as differential analysis, response surface methodology, Monte Carlo analysis, and variance decomposition procedures [1]. Zhang et al. [21] established the geometric error cost model and geometric error reliability model based on the traditional cost model and reliability analysis model, considering the principle of the weighting function. Then, an error allocation method is proposed to optimize the total cost and the reliability. Cheng et al. [6] developed an error allocation method based on the first-order second-moment method to optimize the allocation of manufacturing and assembly tolerances while specifying operating conditions to determine the optimal level of these errors. Based on Monte Carlo simulation method, the reliability and sensitivity analysis models of machining accuracy for machine tools are given by Cheng et al [8]. The machining accuracy reliability is taken as the index to measure the capability of the machine tools, and the reliability sensitivity is taken as the reference to optimize the basic parameters of the machine tools. The validity of this method is verified by taking a three-axis machine tool as an example. In this paper, the reliability model of machining accuracy is established by updating primary reliability based on an important sampling method, which can determine the reliability of grinding machines at different machining locations. Different geometric errors have different effects on the reliability of machining accuracy of machine tools. How to find and control the key geometric errors effectively is the main problem to improve the machining accuracy [15]. Through sensitivity analysis of machining accuracy reliability, the most critical geometric errors can be identified. Lee and Lin studied the effect of each assembly error term on the volumetric error of a five-axis machine tool according to form-shaping theory [13]. Chen [4] studies the volumetric error modeling and its sensitivity analysis for the purpose of machine design. Cheng [7] considered the stochastic characteristic of geometric errors and used Sobol's global sensitivity analysis method to identify crucial geometric errors of machine tools, which is helpful to improve the machining accuracy of multi-axis machine tools. In this paper, the improved first-order second-moment method is used to establish a sensitivity analysis model, which can identify and optimize the main geometric error parameters that affect the machining accuracy reliability, so that the machining accuracy reliability of machine tools can meet the design requirements. In this paper, the principle of differential motion between coordinate frames is applied to geometric error modeling of machine tools, and a new precision design method is proposed by combining with reliability theory. It has important theoretical significance and practical value for further study machining precision reliability of machine tools.

Differential motion vector in a rigid body or coordinate frame include differential translation vector and differential rotation vector [9]. The differential translation consists of the differential movement of the coordinate frame in the direction of three coordinate axes, and the differential rotation consists of the differential rotation of the coordinate frame around three coordinate axes, then the differential motion vector of the coordinate frame is expressed as:

$$E = [\delta_x, \delta_y, \delta_z, \varepsilon_x, \varepsilon_y, \varepsilon_z] \tag{1}$$

According to the differential motion relation in coordinate system, the differential motion in one coordinate frame can be represented in another coordinate frame. The differential changes relationship between the two coordinate frames can be established by a 6 × 6 transformation matrix, which is the differential motion matrix [16]. Assume that the homogeneous transformation matrix of coordinate frame c relative to coordinate frame d is:

$$\mathbf{T}_c^d = \begin{bmatrix} \mathbf{R} & \mathbf{P} \\ \mathbf{O} & 1 \end{bmatrix} = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

Then the differential motion matrix of coordinate frame d relative to coordinate frame c can be expressed as:

$$DJ\left[\mathbf{T}_c^d\right] = \begin{bmatrix} \mathbf{R}^{\mathrm{T}} & -\mathbf{R}^{\mathrm{T}}(\mathbf{P}\times) \\ \mathbf{O}_{3\times3} & \mathbf{R}^{\mathrm{T}} \end{bmatrix} = \begin{bmatrix} n_x & n_y & n_z & (p\times n)_x & (p\times n)_y & (p\times n)_z \\ o_x & o_y & o_z & (p\times o)_x & (p\times o)_y & (p\times o)_z \\ a_x & a_y & a_z & (p\times a)_x & (p\times a)_y & (p\times a)_z \\ 0 & 0 & 0 & n_x & n_y & n_z \\ 0 & 0 & 0 & o_x & o_y & o_z \\ 0 & 0 & 0 & a_x & a_y & a_z \end{bmatrix} \tag{3}$$

where ($\boldsymbol{P}\times$) represents the skew-symmetric matrix of vector $\boldsymbol{P}$.

Differential motion matrix reflects the transfer relationship of differential motion between coordinate frames. If the differential motion vector of the coordinate frame d is:

$$\Delta\mathbf{E}_d = \left[\delta_{xd}, \delta_{yd}, \delta_{zd}, \varepsilon_{xd}, \varepsilon_{yd}, \varepsilon_{zd}\right]^{\mathrm{T}} \tag{4}$$

Then the differential motion vector of the coordinate frame c caused by the differential motion of the coordinate frame d as follows:

$$\Delta\mathbf{E}_d^c = DJ\left[\mathbf{T}_c^d\right] \cdot \Delta\mathbf{E}_d \tag{5}$$

The rest of the paper is organized as follows. In Sect. 2, a comprehensive geometric error model of a machine tool is established based on differential motion relationship between coordinate systems. In Sect. 3, a general precision allocation method that includes machine tools reliability prediction and error parameter optimization is proposed. Furthermore, the effectiveness of the method is validated by a large CNC gantry guide rail grinder. The conclusions are presented in Sect. 4.

2. Geometric error modeling of machine tool based on the differential motion relation of coordinate frames

2.1. Differential motion matrix of a machine tool

When the differential transformation between coordinate frames is applied to geometric error modeling of a machine tool, the influence of geometric errors of various parts of a machine tool on machining accuracy can be obtained and geometric error model can be established. Taking a large CNC gantry rail grinder as an example, the geometric error modeling process of this machine tool is presented using differential motion relation of coordinate frames.

The basis of geometric error modeling is to obtain the homogeneous transformation matrices between each component of the machine tool. Firstly, the homogeneous transformation matrices of tool relative to any other component are established according to the order of open kinematic chain of the machine tool. The structure of the large CNC gantry rail grinder is shown in Figure 1 and the corresponding topological structure is shown in Figure 2. The order of open kinematic chain is working table — *X*-axis — Bed — *Z*-axis — *Y*-axis — tool.

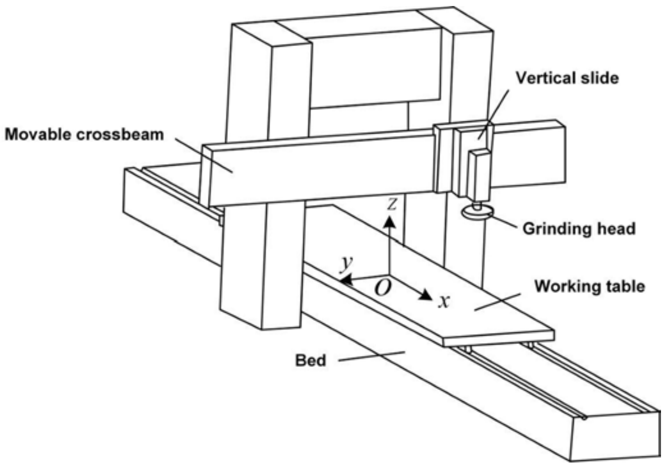

Fig. 1. Structure diagram of CNC gantry guide rail grinder

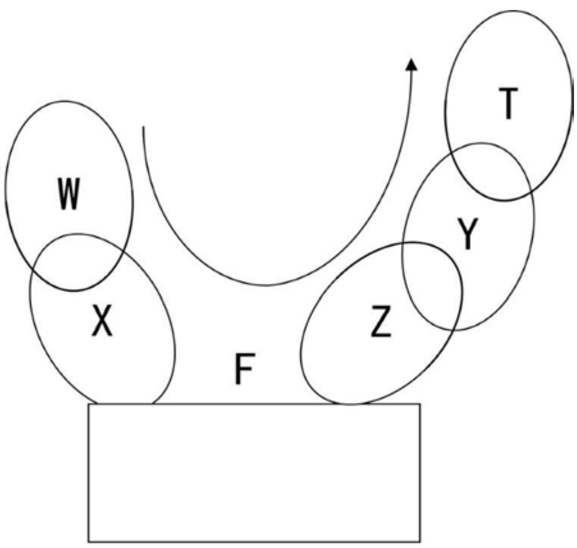

Fig. 2. Topological structure diagram

The components of the grinder are regarded as rigid bodies and their local coordinate frames are established. Based on the MBS theory, the homogeneous transformation matrices between the components of the grinder are established. The homogeneous transformation matrices of the working table relative to *X*-axis, the *X*-axis relative to bed, the *Z*-axis relative to bed, the *Y*-axis relative to *Z*-axis, and the tool relative to *Y*-axis are respectively represented as:

$$\mathbf{T}_W^X = \mathbf{E} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \mathbf{T}_X^F = \begin{bmatrix} 1 & 0 & 0 & x \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \mathbf{T}_Z^F = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & z \\ 0 & 0 & 0 & 1 \end{bmatrix},$$
$$\mathbf{T}_Y^Z = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & y \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \mathbf{T}_T^Y = \mathbf{E} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6}$$

Then the homogeneous transformation matrix of the bed relative to the *X*-axis coordinate frame can be indicated as:

$$\mathbf{T}_F^X = \begin{bmatrix} 1 & 0 & 0 & -x \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{7}$$

where x, y, and z denote the moving distances of the *X*-axis, *Y*-axis and *Z*-axis respectively.

From the order of open kinematic chain of the grinder, the homogeneous transformation matrices of the tool relative to other parts of the grinder can be obtained, which are expressed as:

$$\begin{cases} \mathbf{T}_T^W = \mathbf{T}_X^W \cdot \mathbf{T}_F^X \cdot \mathbf{T}_Z^F \cdot \mathbf{T}_Y^Z \cdot \mathbf{T}_T^Y \\ \mathbf{T}_T^X = \mathbf{T}_F^X \cdot \mathbf{T}_Z^F \cdot \mathbf{T}_Y^Z \cdot \mathbf{T}_T^Y \\ \mathbf{T}_T^F = \mathbf{T}_Z^F \cdot \mathbf{T}_Y^Z \cdot \mathbf{T}_T^Y \\ \mathbf{T}_T^Z = \mathbf{T}_Y^Z \cdot \mathbf{T}_T^Y \\ \mathbf{T}_T^Y = \mathbf{T}_T^Y \end{cases} \tag{8}$$

From equations (3) and (8), the differential motion matrices of each axis of the grinder relative to the tool can be obtained, which are:

$$DJ\left[\mathbf{T}_X^T\right] = \begin{bmatrix} 1 & 0 & 0 & 0 & z & -y \\ 0 & 1 & 0 & -z & 0 & -x \\ 0 & 0 & 1 & y & x & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{9}$$

$$DJ\left[\mathbf{T}_Z^T\right] = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & -y \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & y & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{10}$$

$$DJ\left[\mathbf{T}_Y^T\right] = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{11}$$

2.2. Error modeling

There are 21 geometric errors in the grinder, including three linear errors and three angular errors of each axis, and three squareness errors. In Figure 3, δ_{xx}, δ_{yx}, δ_{zx} represent the linear error of X-axis in the x, y, and z-directions, ε_{xx}, ε_{yx}, ε_{zx} represent the angular errors of X-axis in the x, y, and z-directions.

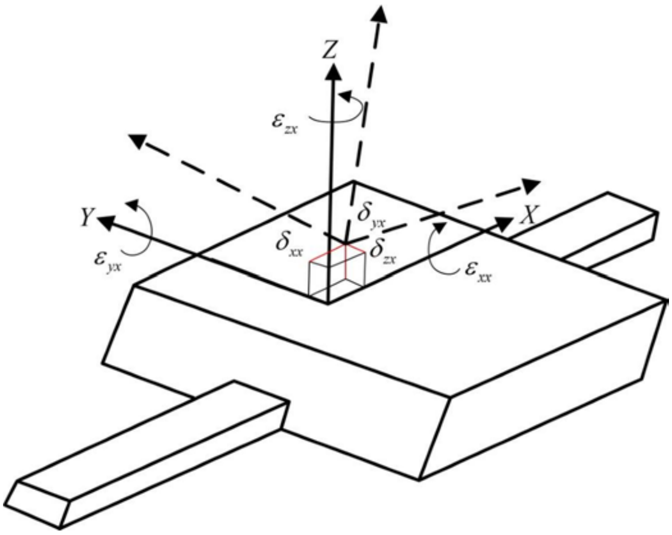

Fig. 3. Basic geometric error of X-axis

In Figure 4, S_{xz}, S_{yz}, S_{xy} represent the squareness errors between the X-axis and Z-axis, Y-axis and Z-axis, X-axis and Y-axis.

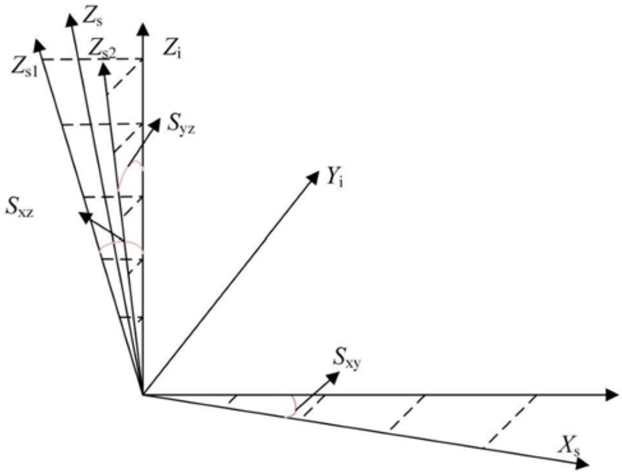

Fig. 4. Distribution of perpendicularity error between triaxial

The geometric errors of each part of the grinder can be regarded as the differential motion of each part in its coordinate system. Linear errors are expressed as differential translation, and angular errors are expressed as differential rotation. The six basic errors will change with the motion of the grinder, and the differential motion vector of each component i can be expressed by:

$$\Delta\mathbf{E}_i = \left[\delta_{xi}, \delta_{yi}, \delta_{zi}, \varepsilon_{xi}, \varepsilon_{yi}, \varepsilon_{zi}\right]^{\mathrm{T}} \tag{12}$$

There is no geometric error in working table and bed, so the differential motion vectors of the working table and bed are as follows:

$$\Delta E_W = [0,0,0,0,0,0]^{\mathrm{T}},\ \Delta E_F = [0,0,0,0,0,0]^{\mathrm{T}} \tag{13}$$

The squareness errors are an important part of the geometric error of machine tools. In the process of error modeling, the squareness errors can be regarded as the angular errors of the corresponding axis. S_{xy} can be regarded as the angular error of the X-axis in the z-direction, S_{xz} can be regarded as the angular error of the Z-axis in the y-direction, S_{yz} can be regarded as the angular error of the Z-axis in the x-direction. Then the differential motion vectors of the Z-axis and Y-axis can be given by:

$$\begin{cases} \Delta\mathbf{E}_Y = \left[\delta_{xy}, \delta_{yy}, \delta_{zy}, \varepsilon_{xy}, \varepsilon_{yy}, \varepsilon_{zy}\right]^{\mathrm{T}} \\ \Delta\mathbf{E}_Z = \left[\delta_{xz}, \delta_{yz}, \delta_{zz}, \left(\varepsilon_{xz} + S_{yz}\right), \left(\varepsilon_{yz} + S_{xz}\right), \varepsilon_{zz}\right]^{\mathrm{T}} \end{cases} \tag{14}$$

When the grinder is seen as one open kinematic chain, the reference coordinate frame is located on the working table, and the geometric errors direction of the part between the bed and the working table are opposite to the direction defined in the measurement, so the differential motion vector of the X-axis is denoted as:

$$\Delta\mathbf{E}_X = \left[-\delta_{xx}, -\delta_{yx}, -\delta_{zx}, -\varepsilon_{xx}, -\varepsilon_{yx}, -\left(\varepsilon_{zx} + S_{xy}\right)\right]^{\mathrm{T}} \tag{15}$$

With the differential motion matrices of each part relative to the tool and the differential motion vectors of each part, the differential motion vectors of the geometric errors of each part in the tool coordinate frame can be obtained. By taking Eqs (9) and (15) into Eq (5), the differential motion vector of geometric error of the X-axis in tool coordinate frame can be got as:

$$\Delta\mathbf{E}_X^T = DJ\left[\mathbf{T}_T^X\right]\cdot\Delta\mathbf{E}_X = \begin{bmatrix} -\delta_{xx} - z\varepsilon_{yx} + y\left(\varepsilon_{zx} + S_{xy}\right) \\ -\delta_{yx} + z\varepsilon_{xx} + x\left(\varepsilon_{zx} + S_{xy}\right) \\ -\delta_{zx} - y\varepsilon_{xx} - x\varepsilon_{yx} \\ -\varepsilon_{xx} \\ -\varepsilon_{yx} \\ -\varepsilon_{zx} \end{bmatrix} \tag{16}$$

In the same way, the differential motion vectors of the geometric errors of the Y-axis and Z-axis in the tool coordinate frame can also be obtained:

$$\Delta\mathbf{E}_Z^T = DJ\left[\mathbf{T}_T^Z\right]\cdot\Delta\mathbf{E}_Z = \begin{bmatrix} \delta_{xz} - y\varepsilon_{zz} \\ \delta_{yz} \\ \delta_{zz} + y\left(\varepsilon_{xz} + S_{yz}\right) \\ \varepsilon_{xz} + S_{yz} \\ \varepsilon_{yz} + S_{xz} \\ \varepsilon_{zz} \end{bmatrix},\ \Delta\mathbf{E}_Y^T = DJ\left[\mathbf{T}_T^Y\right]\cdot\Delta\mathbf{E}_Y = \begin{bmatrix} \delta_{xy} \\ \delta_{yy} \\ \delta_{zy} \\ \varepsilon_{xy} \\ \varepsilon_{yy} \\ \varepsilon_{zy} \end{bmatrix} \tag{17}$$

And then, by adding the differential motion vectors of the geometric errors of the components in the tool coordinate frame, the comprehensive error vector of the tool can be obtained, which shows the influence of the geometric errors of the components on the tool coordinate frame:

$$\Delta\mathbf{E}_T=\Delta\mathbf{E}_X^T+\Delta\mathbf{E}_Z^T+\Delta\mathbf{E}_Y^T=\begin{bmatrix}-\delta_{xx}-z\varepsilon_{yx}+y\varepsilon_{zx}+\delta_{xz}+\delta_{xy}+yS_{xy}\\-\delta_{yx}+z\varepsilon_{xx}+x\varepsilon_{zx}+\delta_{yz}+\delta_{yy}+xS_{xy}\\-\delta_{zx}-y\varepsilon_{xx}-x\varepsilon_{yx}+\delta_{zz}+y\varepsilon_{xz}+\delta_{zy}+yS_{yz}\\-\varepsilon_{xx}+\varepsilon_{xz}+S_{yz}+\varepsilon_{xy}\\-\varepsilon_{yx}+\varepsilon_{yz}+S_{xz}+\varepsilon_{yy}\\-\varepsilon_{zx}+\varepsilon_{zz}+\varepsilon_{zy}\end{bmatrix} \tag{18}$$

where ΔE_T is the comprehensive geometric error model of the grinder in the tool coordinate frame.

3. Accuracy distribution

3.1. Reliability modeling of machining accuracy

Reliability refers to the ability of a product to complete specified functions under specified conditions and within the specified time. It is one of the most important quality attributes of components, products, and complex systems [11]. Machining accuracy reliability, which reflects the performance of machine tools to maintain machining accuracy, is considered. To reflect the influence of geometric errors of machine tools on the reliability of machining accuracy, in this paper a method of updating the primary reliability with importance sampling method is proposed and the reliability model of machining accuracy of the grinder is given. Compared with the commonly used sampling method, this method can ensure that the shape of limit state surface is taken into account and sampling is processed in important areas. Consider a limit state function $Z = g_X(\boldsymbol{X}) = g_X(X_1, X_2, \dots, X_n)$ where the random variable $\boldsymbol{X}$ are independent and follow normal distribution, the mean value is $\boldsymbol{\mu}_X = (\mu_{X1}, \mu_{X2}, \dots, \mu_{Xn})$, the variance is $\boldsymbol{\sigma}_X = (\sigma_{X1}, \sigma_{X2}, \dots, \sigma_{Xn})$. Let $\boldsymbol{x}^*$ be a point on the plane of limit state, then:

$$Z = g_X\left(\mathbf{x}^*\right) = 0 \tag{19}$$

To calculate the reliability index, we can use a Taylor series expansion of $Z = g_X(\boldsymbol{X})$ at the point $\boldsymbol{x}^*$ to linearize the limit state function. The Taylor series expansion is:

$$Z_L = g_X(\mathbf{x}^*) + \sum_{i=1}^{n} \frac{\partial g_X\left(\mathbf{x}^*\right)}{\partial X_i}\left(X_i - x_i^*\right) \tag{20}$$

Thus, the reliability index can be obtained as follows:

$$\beta = \frac{\mu_{ZL}}{\sigma_{ZL}} = \frac{g_X\left(\mathbf{x}^*\right) - \sum_{i=1}^{n} \frac{\partial g_X\left(\mathbf{x}^*\right)}{\partial X_i} x_i^*}{\sqrt{\sum_{i=1}^{n}\left[\frac{\partial g_X\left(\mathbf{x}^*\right)}{\partial X_i}\right]^2}} \tag{21}$$

And the sensitivity coefficient of the variable α_{Xi} is also given by:

$$\alpha_{Xi} = -\frac{\frac{\partial g_X(\mathbf{x}^*)}{\partial X_i}\sigma_{Xi}}{\sqrt{\sum_{i=1}^{n}\left[\frac{\partial g_X(\mathbf{x}^*)}{\partial X_i}\right]^2 \sigma^2{}_{Xi}}} \tag{22}$$

Transforming basic random variable $\boldsymbol{X}$ space into independent standard normal random variable $\boldsymbol{Y}$ space, the function becomes $Z = g_Y(\boldsymbol{Y})$. The improved first-order second-moment method is used to solve the reliability index β, design point $\boldsymbol{y}^*$ and sensitivity vector $\boldsymbol{\alpha}_Y = [\alpha_{Y1}, \alpha_{Y2}, \dots, \alpha_{Yn}]^T$ in Y space. Constructing an orthogonal matrix $\boldsymbol{H} = [\boldsymbol{H}_1, \boldsymbol{H}_2, \dots, \boldsymbol{H}_{n-1}, \boldsymbol{\alpha}_Y]$ from $\boldsymbol{\alpha}_Y$ by orthogonal normalization technique. Using $\boldsymbol{H}$ to transform the rotation of $\boldsymbol{Y}$ space into another standard normal variable $\boldsymbol{P}$ space, we can obtain:

$$\mathbf{Y} = \mathbf{HP} = \tilde{\mathbf{H}}\tilde{\mathbf{P}} + P_n\boldsymbol{\alpha}_Y \tag{23}$$

In Equation (23):

$$\tilde{\mathbf{H}} = \left(H_1, H_2, \cdots, H_{n-1}\right),\ \tilde{\mathbf{P}} = \left(P_1, P_2, \cdots, P_{n-1}\right)^{\mathrm{T}} \tag{24}$$

The design point in $\boldsymbol{P}$ space is $\boldsymbol{p}^* = \boldsymbol{H}^{\mathrm{T}}\boldsymbol{y}^*$. The limit state surface $g_P(\boldsymbol{P}) = 0$ is orthogonal to the P_n axis at $\boldsymbol{p}^*$. The positive direction of P_n axis points to the failure region. Therefore, the function can be expressed as:

$$Z = g_P(P) = h_{\tilde{P}}(\tilde{p}) - P_n \tag{25}$$

In the failure domain, $\boldsymbol{P}$ satisfies the following equation:

$$P_n = P_n\left(\tilde{\mathbf{P}}\right) \geq h_{\tilde{P}}\left(\tilde{\mathbf{P}}\right) \tag{26}$$

In $\boldsymbol{P}$ space, the failure probability is:

$$p_f = \int_{g_P(p)\leq 0} \varphi_n(p)\mathrm{d}p = \int_{-\infty}^{+\infty} \Phi\left[-h_{\tilde{P}}(\tilde{p})\right]\varphi_{n-1}(\tilde{p})\mathrm{d}\tilde{p} = E\left\{\Phi\left[-h_{\tilde{P}}(\tilde{p})\right]\right\} \tag{27}$$

Sample $\tilde{\mathbf{p}}_i = \left(i = 1, 2, \cdots, N\right)$ can be obtained by sampling the standard normal random variable $\tilde{\mathbf{P}}$. Therefore, the unbiased estimation of failure probability can be got by:

$$\hat{p}_{\mathrm{f}} = \frac{1}{N}\sum_{i=1}^{N}\Phi\left[-h_{\tilde{P}}\left(\tilde{p}_i\right)\right] \tag{28}$$

The design point $\mathbf{p}^* = \left(\tilde{\mathbf{p}}^{*\mathrm{T}}, p_n^*\right)^{\mathrm{T}}$ satisfies the expression $h_{\tilde{P}}\left(\tilde{\mathbf{p}}^*\right) = p_n^* = \beta$. $\tilde{\mathbf{p}}^*$ was taken as the sampling center. This method updates the results of the improved first-order second-moment method.

The comprehensive error model of grinder in tool coordinate system can be expressed as follows:

$$\Delta\mathbf{E}_T=\begin{bmatrix}-\delta_{xx}-z\varepsilon_{yx}+y\varepsilon_{zx}+\delta_{xz}+\delta_{xy}+yS_{xy}\\-\delta_{yx}+z\varepsilon_{xx}+x\varepsilon_{zx}+\delta_{yz}+\delta_{yy}+xS_{xy}\\-\delta_{zx}-y\varepsilon_{xx}-x\varepsilon_{yx}+\delta_{zz}+y\varepsilon_{xz}+\delta_{zy}+yS_{yz}\\-\varepsilon_{xx}+\varepsilon_{xz}+S_{yz}+\varepsilon_{xy}\\-\varepsilon_{yx}+\varepsilon_{yz}+S_{xz}+\varepsilon_{yy}\\-\varepsilon_{zx}+\varepsilon_{zz}+\varepsilon_{zy}\end{bmatrix}=\left[p_{ex},p_{ey},p_{ez},o_{ex},o_{ey},o_{ez}\right]^{\mathrm{T}} \tag{29}$$

Let $\boldsymbol{I}$ be the maximum allowable error of the grinder, then the limit state function of the grinder is:

$$\mathbf{Z} = \mathbf{I} - \Delta\mathbf{E}_T \tag{30}$$

We can use the value of the limit state function to judge the performance of the grinder. When $Z > 0$, the machine tool is in a reliable state; otherwise, the machine tool is in an unreliable state. The geometric errors of each part of the grinder are generally considered to be normal distribution and independent of each other, so the importance sampling method to updating reliability is suitable for the reliability modeling of machining accuracy of the grinding machine.

3.2. Sensitivity analysis of machining accuracy reliability

The machining accuracy reliability of machine tools is determined by the distribution types and distribution parameters of all design variables, and the sensitivity of different influencing factors to reliability is very different [19]. In this paper, the sensitivity of the grinder is analyzed by improved first-order second-moment method, and the sensitivity of different geometric error parameters to machining accuracy reliability is determined.

The reliability of machining accuracy can be given by the improved first-order second-moment method as follows:

$$R = \Phi(\beta) \tag{31}$$

The partial derivatives of mean and variance of geometric error are given by:

$$\begin{cases} \dfrac{\partial R}{\partial \mu_{xi}} = \dfrac{\partial R}{\partial \beta} \cdot \dfrac{\partial \beta}{\partial \mu_{ZL}} \cdot \dfrac{\partial \mu_{ZL}}{\partial \mu_{xi}} \\ \dfrac{\partial R}{\partial \sigma_{xi}} = \dfrac{\partial R}{\partial \beta} \cdot \dfrac{\partial \beta}{\partial \sigma_{ZL}} \cdot \dfrac{\partial \sigma_{ZL}}{\partial \sigma_{xi}} \end{cases} \tag{32}$$

In equation (32):

$$\begin{cases} \dfrac{\partial R}{\partial \beta} = \dfrac{1}{\sqrt{2\pi}} \exp\left(-\dfrac{\beta^2}{2}\right) \\ \dfrac{\partial \beta}{\partial \mu_{ZL}} = \dfrac{1}{\sigma_{ZL}} \\ \dfrac{\partial \beta}{\partial \sigma_{ZL}} = -\dfrac{\mu_{ZL}}{\sigma^2{}_{ZL}} \\ \dfrac{\partial \mu_{ZL}}{\partial \boldsymbol{\mu}_X^{\mathrm{T}}} = \left[\dfrac{\partial \mu_{ZL}}{\partial \mu_{x1}}, \dfrac{\partial \mu_{ZL}}{\partial \mu_{x2}}, \dots, \dfrac{\partial \mu_{ZL}}{\partial \mu_{xn}}\right]^{\mathrm{T}} \\ \dfrac{\partial \sigma_{ZL}}{\partial \boldsymbol{\sigma}_X^{\mathrm{T}}} = \left[\dfrac{\partial \sigma_{ZL}}{\partial \sigma_{x1}}, \dfrac{\partial \sigma_{ZL}}{\partial \sigma_{x2}}, \dots, \dfrac{\partial \sigma_{ZL}}{\partial \sigma_{xn}}\right]^{\mathrm{T}} \end{cases} \tag{33}$$

So, the reliability sensitivity of machining accuracy of various geometric error parameters is obtained.

Till now, a precision design method has been put forward. It takes into account geometric errors of machine tools, and includes accuracy reliability model and reliability sensitivity model. Its process is shown in Figure 5.

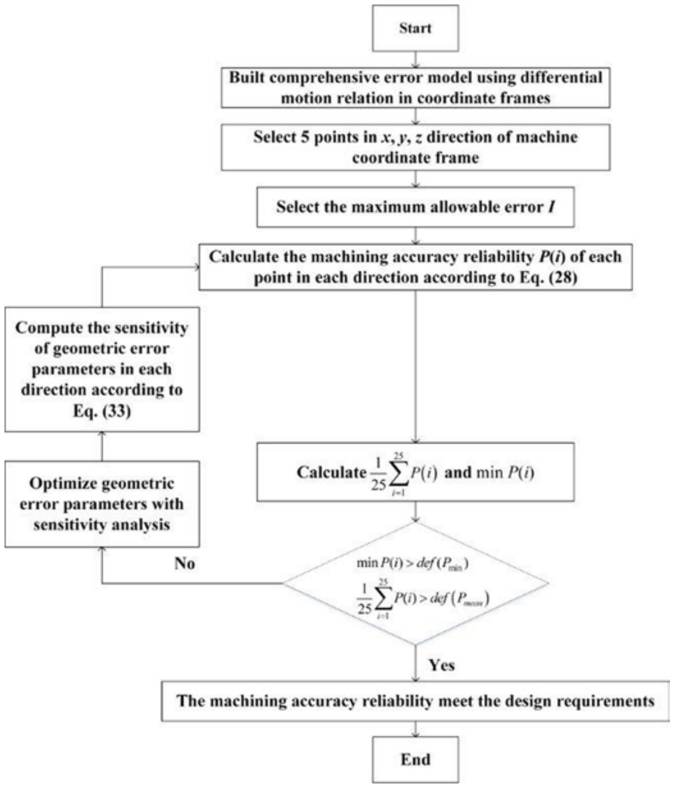

Fig. 5. Flowchart showing the algorithm of the procedure

3.3. Reliability analysis and accuracy optimization of grinder machining accuracy

The geometric errors of various parts of MKW5230A/3×160 large accuracy CNC gantry guideway grinder approximately obey normal distribution, so the 21 of geometric errors are regarded as obeying normal distributions. The variances of the geometric errors are determined by assembly tolerances and geometric tolerances. The mean values of all geometric errors are 0. According to the accuracy of the existing general CNC equipment and the national standard of accuracy testing for gantry guide rail grinder of the people's Republic of China (GB/T5288-2007/ISO4703: 2001), the variances of 21 geometric errors are preliminarily determined [18]. As shown in Table 1.

There are three linear errors and three angular errors in the comprehensive geometric error model of the grinder in the tool coordinate frame. As for the angle error, it can be seen from its expression, mean value, and variance that the three angular errors are far less than the allowable errors, which will not be calculated in this paper. In the tool coordinate frame of the grinder, the minimum value of reliability is not less than 95% and the average value of reliability is not less than 97% within the maximum allowable error $\boldsymbol{I} = [0.03, 0.03, 0.03]^{\mathrm{T}}$. In its working stroke, five points of 0, 250, 500, 750, 1000 are selected in *x*-direction, five points of -1500, -750, 0,750,1500 are selected in *y*-direction, and five points of 600,800,1000,1200,1400 are selected in *z*-direction. Using the method proposed in this paper, the machining accuracy reliability of each point can be calculated with Matlab program.

Table 1. Variance of 21 geometric errors

Error variable (1-7)	δ_{xx}	δ_{yx}	δ_{zx}	ε_{xx}	ε_{yx}	ε_{zx}	δ_{xy}
variance /mm	0.05/6	0.05/6	0.05/6	0.03/6000	0.06/6000	0.05/6000	0.04/6
Error variable (8-14)	δ_{yy}	δ_{zy}	ε_{xy}	ε_{yy}	ε_{zy}	δ_{xz}	δ_{yz}
variance /mm	0.05/6	0.04/6	0.05/6000	0.04/6000	0.04/6000	0.03/6	0.03/6
Error variable (15-21)	δ_{zz}	ε_{xz}	ε_{yz}	ε_{zz}	S_{xy}	S_{xz}	S_{yz}
variance /mm	0.05/6	0.03/6000	0.04/6000	0.03/6000	0.03/3000	0.03/3000	0.02/3000

The limit state equations of the grinder in x, y, and z-directions are given as follows:

$$P_{ex} = 0.03 - \left(-\delta_{xx} - z\varepsilon_{yx} + y\varepsilon_{zx} + \delta_{xz} + \delta_{xy} + yS_{xy}\right)$$
$$P_{ey} = 0.03 - \left(-\delta_{yx} + z\varepsilon_{xx} + x\varepsilon_{zx} + \delta_{yz} + \delta_{yy} + xS_{xy}\right) \quad (34)$$
$$P_{ez} = 0.03 - \left(-\delta_{zx} - y\varepsilon_{xx} - x\varepsilon_{yx} + \delta_{zz} + y\varepsilon_{xz} + \delta_{zy} + yS_{yz}\right)$$

In equation (34), P_{ex} is only related to *Y*-axis and *Z*-axis coordinates. P_{ey} is only related to *X*-axis and *Z*-axis coordinates. P_{ez} is only related to *X*-axis and *Y*-axis coordinates. The reliability of machining accuracy in different directions at selected points is shown in Tables 2 ~ 4.

It can be seen from Table 2 that the minimum reliability value of 25 machining accuracy items in the *x*-direction is 86.07%, and the average reliability value is 92.16%. In Table 3, it also can be seen that

Table 2. Reliability of machining accuracy in the x-direction

Vector of point (*y*, *z*)	(-1500, 600)	(-750, 600)	(0, 600)	(750, 600)	(1500, 600)
Reliability (%)	88.83	96.14	98.74	96.14	88.83
Vector of point (*y*, *z*)	(-1500, 800)	(-750, 800)	(0, 800)	(750, 800)	(1500, 800)
Reliability (%)	88.31	95.42	98.14	95.42	88.31
Vector of point (*y*, *z*)	(-1500, 1000)	(-750, 1000)	(0, 1000)	(750, 1000)	(1500, 1000)
Reliability (%)	87.67	94.51	97.28	94.51	87.67
Vector of point (*y*, *z*)	(-1500, 1200)	(-750, 1200)	(0, 1200)	(750, 1200)	(1500, 1200)
Reliability (%)	86.93	93.41	96.17	93.41	86.93
Vector of point (*y*, *z*)	(-1500, 1400)	(-750, 1400)	(0, 1400)	(750, 1400)	(1500, 1400)
Reliability (%)	86.07	92.36	94.74	92.36	86.07

Table 3. Reliability of machining accuracy in the y-direction

Vector of point (*x*, *z*)	(0, 600)	(0, 800)	(0, 1000)	(0, 1200)	(0, 1400)
Reliability (%)	98.85	98.64	98.46	98.12	97.81
Vector of point (*x*, *z*)	(250, 600)	(250, 800)	(250, 1000)	(250, 1200)	(250, 1400)
Reliability (%)	98.44	98.28	98.10	97.96	97.65
Vector of point (*x*, *z*)	(500, 600)	(500, 800)	(500, 1000)	(500, 1200)	(500, 1400)
Reliability (%)	97.85	97.59	97.28	96.97	96.59
Vector of point (*x*, *z*)	(750, 600)	(750, 800)	(750, 1000)	(750, 1200)	(750, 1400)
Reliability (%)	96.53	96.28	95.94	95.75	95.33
Vector of point (*x*, *z*)	(1000, 600)	(1000, 800)	(1000, 1000)	(1000, 1200)	(1000, 1400)
Reliability (%)	94.64	94.39	94.05	93.92	93.45

Table 4. Reliability of machining accuracy in the z-direction

Vector of point (*x*, *y*)	(0, -1500)	(0, -750)	(0, 0)	(0, 750)	(0, 1500)
Reliability (%)	93.53	96.44	98.54	96.44	93.53
Vector of point (*x*, *y*)	(250, -1500)	(250, -750)	(250, 0)	(250, 750)	(250, 1500)
Reliability (%)	93.38	97.18	98.43	97.18	93.38
Vector of point (*x*, *y*)	(500, -1500)	(500, -750)	(500, 0)	(500, 750)	(500, 1500)
Reliability (%)	92.93	96.71	98.01	96.71	92.93
Vector of point (*x*, *y*)	(750, -1500)	(750, -750)	(750, 0)	(750, 750)	(750, 1500)
Reliability (%)	92.21	95.89	97.28	95.89	92.21
Vector of point (*x*, *y*)	(1000, -1500)	(1000, -750)	(1000, 0)	(1000, 750)	(1000, 1500)
Reliability (%)	91.21	94.82	96.14	94.82	91.21

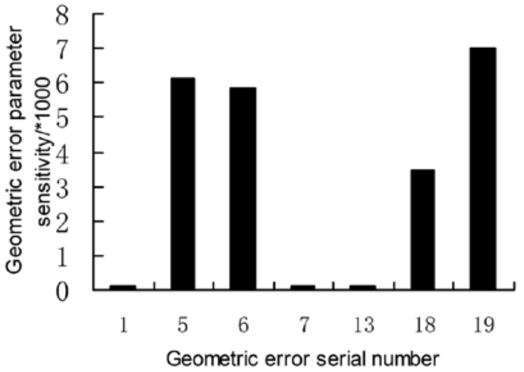

Fig. 6. Geometric error parameter sensitivity in the x-direction

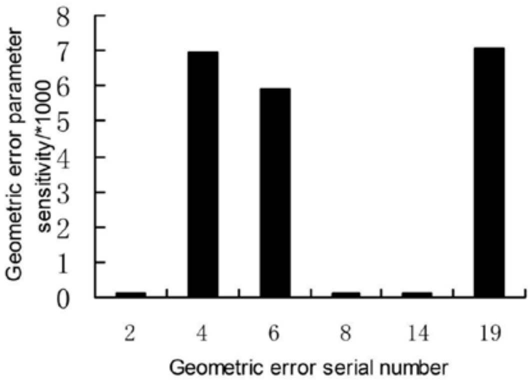

Fig. 7. Geometric error parameter sensitivity in the y-direction

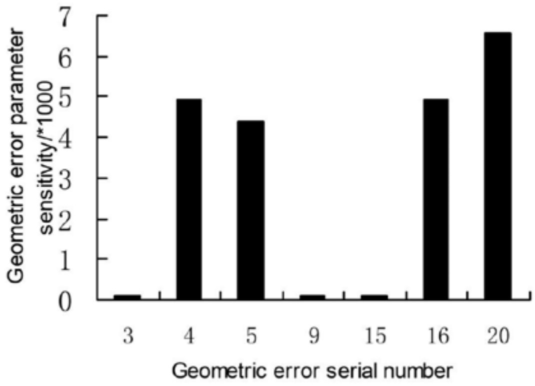

Fig. 8. Geometric error parameter sensitivity in the z-direction

Table 5. The reliability after improvement in the x-direction

Improvement times	Error variable				Reliability	
	ε_{yx}	ε_{zx}	ε_{zz}	S_{xy}	mean value (%)	minimum value (%)
Initial value/mm	0.06/6000	0.05/6000	0.03/6000	0.03/3000	92.16	86.07
The first improvement/mm	0.055/6000	0.045/6000	0.025/6000	0.025/3000	93.66	88.49
The second improvement/mm	0.05/6000	0.04/6000	0.02/6000	0.02/3000	95.15	91.01
The third improvement/mm	0.045/6000	0.035/6000	0.015/6000	0.015/3000	96.46	93.43
The fourth improvement/mm	0.04/6000	0.03/6000	0.01/6000	0.01/3000	97.76	96.52

Table 6. The reliability after improvement in the y-direction

Improvement times	Error variable			Reliability	
	ε_{xx}	ε_{zx}	S_{xy}	Mean value (%)	Minimum value (%)
Initial value/mm	0.03/6000	0.05/6000	0.03/3000	96.75	93.45
The first improvement/mm	0.025/6000	0.045/6000	0.025/3000	97.23	94.65
The second improvement/mm	0.02/6000	0.04/6000	0.02/3000	97.68	95.55

the minimum reliability value of 25 machining accuracy items in the *y*-direction is 93.45%, and the average reliability value is 96.75%. In Table 4, it also can be seen that that the minimum reliability value of 25 machining accuracy items in the *z*-direction is 91.21%, and the average reliability value is 95.08%. The minimum and mean values of reliability in all directions do not meet the design requirements. The reliability sensitivity analysis method based on the improved first-order second-moment method is used to determine the geometric error parameters. Because the mean value of each geometric error is 0, only the geometric error variance is analyzed. Figures 6-8 shows the sensitivity of geometric error variance in each direction. It can be seen that the geometric errors in the *x*-direction are ε_{yx}, ε_{zx}, ε_{zz}, S_{xy}. For *y*-direction, they are ε_{xx}, ε_{zx}, S_{xy}. For *z*-direction, they are ε_{xx}, ε_{yx}, ε_{xz}, S_{yz}.

The reliability of machining accuracy can be improved by adjusting the geometric errors with a higher sensitivity. Tables 5-7 show the results after improvement.

From Tables 5-7, it can be seen that the minimum and average values of machining accuracy reliability in *x*, *y* and *z* directions meet the design requirements by optimizing geometric error parameters with high sensitivity. Therefore, it can be concluded that the reliability model and sensitivity model presented in this paper are feasible and effective when the geometric error distribution types and distribution parameters of machine tools are known. The reliability calculation method proposed in this paper incorporates stochastic simulation and statistical analysis, which can solve the reliability problem with high non-linearity. In fact, CNC machine tools is a complex mechanical equipment with a highly nonlinearity. Therefore, this method is more suitable for analyzing the machining accuracy of machine tools.

4. Conclusion

In this paper, a general precision design method for CNC machine tools is proposed. The method takes average value and minimum value of machining precision reliability as constraints, and combines sensi-

Table 7. The reliability after improvement in the z-direction

Improvement times	Error variable				Reliability	
	ε_{xx}	ε_{yx}	ε_{xz}	S_{yz}	Mean value (%)	Minimum value (%)
Initial value/mm	0.06/6000	0.05/6000	0.03/6000	0.03/3000	95.08	91.21
The first improvement/mm	0.055/6000	0.045/6000	0.025/6000	0.025/3000	96.24	93.26
The second improvement/mm	0.05/6000	0.04/6000	0.02/6000	0.02/3000	97.06	94.69
The third improvement/mm	0.045/6000	0.035/6000	0.015/6000	0.015/3000	97.21	95.24

tivity analysis of error parameters to optimize geometric error parameters of machine tools. Some conclusions are drawn as follows:

1. Compared with the existing traditional method, the geometric error modeling method based on the differential motion relation between coordinate frames has less calculation and can clearly explain the geometric meaning of the geometric error of each part to the total error.
2. Based on the comprehensive error model and advanced importance sampling method, the accuracy reliability model and reliability sensitivity model of machine tools are given to optimize the machining accuracy reliability of machine tools.
3. The effectiveness of the method proposed in this paper is validated by a large CNC gantry guide rail grinder, the results show that the machining accuracy reliability of the machine tool can be improved.

References

1. Antonio CC, Hoffbauer LN. An approach for reliability-based robust design optimisation of angle-piy composite. Composite Structures 2009; 90(1): 53-59, https://doi.org/10.1016/j.compstruct.2009.01.008.
2. Bohez ELJ, Ariyajunya B, Sinlapeecheewa C, Shein TMM, Lap DT, Belforte G. Systematic geometric rigid body error identification of 5-axis milling machines. Computer-Aided Design 2007; 39(4): 229-244, https://doi.org/10.1016/j.cad.2006.11.006.
3. Cai LG, Zhang ZL, Cheng Q, Liu ZF, Gu PH. A geometric accuracy design method of multi-axis NC machine tool for improving machining accuracy reliability. Eksploatacja i Niezawodnosc-Maintenance and Reliability 2015; 17(1): 143-155, https://doi.org/10.17531/ein.2015.1.19.
4. Chen GD, Liang YC, Sun YZ, Chen WQ, Wang B. Volumetric error modeling and sensitivity analysis for designing a five-axis ultra-precision machine too. The International Journal of Advanced Manufacturing Technology 2013; 68(9-12): 2525-2534, https://doi.org/10.1007/s00170-013-4874-4.
5. Cheng Q, Feng QN, Liu ZF, Gu PH, Cai LG. Fluctuation prediction of machining accuracy for multi-axis machine tool based on stochastic process theory. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science 2015; 229(14): 2534-2550, https://doi.org/10.1177/0954406214562633.
6. Cheng Q, Zhang ZL, Zhang GJ, Gu PH, Cai LG. Geometric accuracy allocation for multi-axis CNC machine tools based on sensitivity analysis and reliability theory. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science 2015; 229(6): 1134-1149, https://doi.org/10.1177/0954406214542491.
7. Cheng Q, Zhao HW, Zhang GJ, Gu PH, Cai LG. An analytical approach for crucial geometric errors identification of multi-axis machine tool based on global sensitivity analysis. The International Journal of Advanced Manufacturing Technology 2014; 75(1-4): 107-121, https://doi.org/10.1007/s00170-014-6133-8.
8. Cheng Q, Zhao HW, Zhao YS, Sun BW, Gu PH. Machining accuracy reliability analysis of multi-axis machine tool based on Monte Carlo simulation. Journal of Intelligent Manufacturing 2018; 29(1): 1-19, https://doi.org/10.1007/s10845-015-1101-1.
9. Fu GQ, Fu JZ, Xu YT, Chen ZC, Lai JT. Accuracy enhancement of five-axis machine tool based on differential motion matrix: Geometric error modeling, identification and compensation. International Journal of Machine Tools & Manufacture 2015; 89: 170-181, https://doi.org/10.1016/j.ijmachtools.2014.11.005.
10. Guo SJ, Mei XS, Jiang GD. Geometric accuracy enhancement of five-axis machine tool based on error analysis. The International Journal of Advanced Manufacturing Technology 2019; 105(1-4): 137-153, https://doi.org/10.1007/s00170-019-04030-4.
11. Huang B. Reliability theory of engineering structure and its application. Wuhan: Wuhan University of Technology Press 2019.
12. Lee ES, Suh SH, Shon JW. A comprehensive method for calibration of volumetric positioning accuracy of CNC-machines. The International Journal of Advanced Manufacturing Technology 1998; 14(1): 43-49, https://doi.org/10.1007/BF01179416.
13. Lee RS, Lin YH. Applying bidirectional kinematics to assembly error analysis for five-axis machine tools with general orthogonal configuration. The International Journal of Advanced Manufacturing Technology 2012; 62(9-12): 1261-1272, https://doi.org/10.1007/s00170-011-3860-y.
14. Niu P, Cheng Q, Chang WF, Song XM, Li YS. Sensitivity analysis of machining accuracy reliability considering partial correlation of geometric errors for Horizontal Machining Center. Proceedings of the Institution of Mechanical Engineers, part B 2021; 235(3): 455-465, https://doi.org/10.1177/0954405420958843.
15. Niu P, Cheng Q, Liu ZF, Chu HY. A machining accuracy improvement approach for a horizontal machining center based on analysis of geometric error characteristics. The International Journal of Advanced Manufacturing Technology 2021; 112: 2873-2887, https://doi.org/10.1007/s00170-020-06565-3.
16. Qi J, Yang W. Differential change construction based geometric error compensation for machine tools. Transactions of the Chinese Society for Agricultural Machinery 2016; 47(9): 398-405.
17. Wu HR, Zheng HL, Li XX, Wang WK, Xiang XP, Meng XP. A geometric accuracy analysis and tolerance robust design approach for a vertical machining center based on the reliability theory. Measurement 2020; 161: 107809, https://doi.org/10.1016/j.measurement.2020.107809.
18. Yu ZM, Liu ZJ, Ai YD, Xiong M. Geometric error model and precision distribution based on reliability theory for large CNC gantry

guideway grinder. Journal of Mechanical Engineering 2013; 49(17): 142-151, https://doi.org/10.3901/JME.2013.17.142.
19. Zhang C. Geometric error inversion and optimization of multi axis CNC machine tools based on robust design. Beijing: Beijing University of Technology 2014.
20. Zhang ZL, Cai LG, Cheng Q, Liu ZF, Gu PH. A geometric error budget method to improve machining accuracy reliability of multi-axis machine tools. Journal of Intelligent Manufacturing 2019; 30(2): 495-519, https://doi.org/10.1007/s10845-016-1260-8.
21. Zhang ZL, Liu ZF, Cai LG, Cheng Q, Qi Y. An accuracy design approach for a multi-axis NC machine tool based on reliability theory. The International Journal of Advanced Manufacturing Technology 2016; 91(5-8): 1-20, https://doi.org/10.1007/s00170-016-9824-5.
22. Zhang ZL, Liu ZF, Cheng Q, Qi Y, Cai LG. An approach of comprehensive error modeling and accuracy allocation for the improvement of reliability and optimization of cost of a multi-axis NC machine tool. The International Journal of Advanced Manufacturing Technology 2016; 89(1-4): 1-19, https://doi.org/10.1007/s00170-016-8981-x.
23. Zhao CB. Application of SCM and PLC technology in CNC machine tool. Applied Mechanics and Materials 2014; 687-691: 22-25, https://doi.org/10.4028/www.scientific.net/AMM.687-691.22.